# Examination of the low frequency limit for helicopter noise data in the Federal Aviation Administration's Aviation Environmental Design Tool and Integrated Noise Model

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## ABSTRACT

The Federal Aviation Administration (FAA) aircraft noise modeling tools Aviation Environmental Design Tool (AEDT[c]) and Integrated Noise Model (INM) do not currently consider noise below 50 Hz in their computations. This paper describes a preliminary study to determine the effect of including low-frequency data on the accuracy of AEDT/INM results. Expanded aircraft noise spectra containing one-third octave band data to 12.5 Hz were analyzed using methods adapted from AEDT/INM. Results from expanded spectral data are compared with results from the historical AEDT/INM spectral data (one-third octave band data from 50 Hz to 10 kHz). This comparison showed a range of differences, from increases in overall un-weighted sound pressure levels (SPL), to negligible changes in A-weighted and Time Audible metrics. These changes may be particularly important for helicopters, with dominant low-frequency rotor noise below 50 Hz. Following the comparison, the potential implementation of expanded spectral data in AEDT is discussed.

## 1. TASK OVERVIEW

This research task is subdivided into three parts. First, the helicopter data for this analysis are selected and processed. This effort included the identification of existing helicopter data sets containing spectral data in the range between 12.5 Hz and 10 kHz; the examination of these frequency data, including blade-pass frequency; and the creation and comparison of Noise-Power-Distance curves (NPDs) from both standard- and expanded-spectra data sets. Second, the effects of expanded spectral data sets on individual frequency-dependant noise computations are analyzed. This analysis includes an investigation into the impact of the expanded spectral data on the frequency-based adjustment and a comparison with corresponding, historical AEDT/INM data. Finally, verification and validation studies integrating the individual effects will be completed.

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[c] AEDT is being developed as the next-generation replacement for INM.

Three helicopters were investigated in this sub-task: Helicopter A is a four-blade, single engine civil helicopter with a seating capacity of seven, including the pilot; Helicopter B is a two-blade, single-engine light civil helicopter with a seating capacity of four, including the pilot; and Helicopter C is a three-blade, single engine light civil helicopter with a seating capacity of two, including the pilot.. All three helicopters have main-rotor blade-pass frequencies within the frequency range of interest, between 12.5 and 50 Hz (see Table 1). Helicopter A is substantially larger than Helicopter B or C, with a maximum gross weight of more than double the next largest helicopter, Helicopter B. During aircraft source measurements for AEDT/INM, noise data were captured from one-third octave frequency bands 11-43, covering the nominal center frequency range from 12.5 to 20,000 Hz[3]. Current INM noise computations do not include noise data in Bands 11-16 and 41-43 (12.5 to 40 Hz and 12,500 to 20,000 Hz, respectively). In this paper, these historical AEDT/INM spectra are referred to as standard spectra, while the spectral data ranging over the bands 11-40 is referred to as expanded spectra.

Inclusion of Bands 11-16 in a plot of one-third octave band levels (see Figure 1) illustrates the dominance of main-rotor blade-pass frequency in the low frequency regime. Smaller increases at harmonic frequencies of BPF can also be seen.

## 2. COMPARISON OF NOISE DATA

### A. Overall Sound Pressure Levels

Sound pressure levels (SPL) were computed from both the standard and expanded spectra and compared. This was done for both dynamic operations (departure, approach, level flight) (see Table 2) and static operations (hover, idle) (see Table 3). Overall, the computed SPL values for the extended spectra were higher than the SPL values for the standard spectra during dynamic events for all aircraft. Un-weighted dynamic event spectra, as shown in Figure 1, show large increases when using extended spectra, ranging from 1.4 to 6.2 dB across all three helicopters. The Helicopter A departure event showed the maximum increase of 6.2 dB in overall SPL. A-weighted values illustrate small increases across all aircraft, with changes of sound level less than 0.1 dB. C-weighted SPL show greater increases between expanded and standard spectra, with a maximum increase of 4.2 dB for Helicopter A, and an average increase over all dynamic events of 2.2 dB across all three aircraft. Flat, A-, and C-weighted static events such as Ground Idle or Hover In Ground Effect (HIGE) illustrate small differences as well, with changes of less than 0.1 dB between expanded and standard spectra. Currently, INM and AEDT use flat, or unweighted, spectral classes; weightings are applied after specific metric types are selected.

### B. Noise-Power-Distance Curves

Noise-Power-Distance curves were developed from expanded spectral data using the simplified adjustment procedure documented in SAE-AIR-1845 "Procedure for the Computation of Airplane Noise in the Vicinity of Airports[4]". This section focuses on A-weighted NPDs based on the A-weighted Sound Exposure Level (SEL, denoted by the symbol $L_{AE}$) and A-weighted Maximum Sound Level (MXA, denoted by the symbol $L_{Amax}$) metrics; C-weighted NPDs are discussed in Section C.iii), below. Tone-corrected metrics are only defined down to 50 Hz[7], and

therefore this low frequency analysis is not applicable to those metrics. A-weighted SEL and MXA NPDs based on both standard and expanded spectra were compared, and the results show only small changes in value as the source-to-receiver distance increases. Level flight and departure events show changes of less than 0.1 dB, with a few exceptions beyond 10,000 feet, where differences of up to 0.35 dB were noted for Helicopter A. Approach events generally show the greatest difference between standard and expanded spectra, with expanded-spectra NPDs showing increases ranging from less than 0.1 dB up to 0.46 dB at 25,000 feet. Static events show changes of less than 0.1 dB for all helicopters, excepting the Helicopter A HOGE event, where the expanded spectrum produced levels from 0.49 dB to 0.77 dB lower than standard spectrum.

## C.    Frequency-Dependent Calculations

Several AEDT/INM calculations have frequency-sensitive components: atmospheric absorption, line-of-sight blockage, C-weighted metrics, and Time Audible (TAUD). The effects of the extended spectral data on these frequency-dependent computations were analyzed. Since modification of AEDT/INM would be necessary to perform these expanded-spectra calculations, these calculations were made using external tools and adapting the current INM methodology[1] to include the expanded spectral data.

### i)   Atmospheric Absorption

Atmospheric absorption values were calculated using both standard and expanded spectra for seven atmospheric conditions ranging from 40 degrees Fahrenheit, 40 percent humidity, to 90 degrees Fahrenheit, 90 percent humidity. For both Helicopters B and C, the differences between atmospheric absorption for standard and expanded spectra did not exceed 0.1 dB for all of the tested atmospheric conditions.   For Helicopter A, the differences between atmospheric absorption for standard and expanded spectra did not exceed 0.1 dB for most of the tested atmospheric condition. The one exception was the Hover Out of Ground Effect (HOGE) event, where differences of up to -0.19 dB at 10,000 feet were observed for a 40 degrees Fahrenheit, 40 percent humidity atmosphere (see Figure 2). This result differs substantially from those for the Helicopters B and C, where the differences between atmospheric absorption corrections increased with distance. This may be due to the unique NPD and spectral values for the Helicopter A HOGE event, and will be investigated further in future analyses.

### ii)  Line-of-Sight Blockage

The line of sight blockage calculation method described in the INM 7.0 Technical Manual[1] was expanded to calculate Fresnel Numbers for the expanded frequency bands 11-16. The Fresnel Number ($N_0$) equation is frequency dependent and is used to compute barrier effects (see Equation 1). :

$$N_0 = \pm 2 \cdot \left( \frac{\delta_0}{\lambda} \right)$$
(1)

where
  $\delta_0$        path length difference determined by source-barrier-receiver geometry, and
  $\lambda$         wavelength of the sound radiated by the source.

The resulting barrier effect values were used to calculate the overall Line-of-Sight Blockage Adjustment (LOS$_{ADJ}$) over a range of path length difference for a sample helicopter spectral class (see Table 4). Values of path length difference were calculated assuming barrier extension perpendicular to the line of sight, 200 feet from the receiver, with line of sight distance of 1,000 feet between source and receiver. Barrier elevation is defined as the distance a given barrier extends beyond the vector describing the direct line of sight from source to receiver. The calculated LOS$_{ADJ}$ values show differences between standard and expanded spectra ranging from less than 0.1 dB to 2.46 dB[d].

### iii) C-weighted Metrics

C-weighted filtering allows for greater low frequency sensitivity compared to A-weighting. C-weighting is taken into account in AEDT/INM as a frequency-based adjustment to the A-weighted NPDs using the spectral class data. As expected, the inclusion of expanded low frequency noise data has a greater effect on C-weighted metrics. As discussed in Section B, little change is seen in A-weighted values between expanded and standard spectra; however, use of expanded spectra in calculating C-weight adjustments results in greater change, with notable increases in SPL at all AEDT/INM distances. For example, a C-weighted NPD for the Helicopter C level flight event has higher values at every AEDT/INM distance, from 0.71 dB higher at 200 feet to 3.42 dB higher at 25,000 feet (see Figure 3.). Similar increases are seen across all dynamic events; static events show little to no difference when using expanded spectra, due to low sound pressure levels across the low frequency regime for static events. Only the Helicopter A HOGE event shows a static event difference greater than 0.1 dB[e]. As the use of expanded spectra has very little effect (less than 0.1 dB) on the resulting A-weighted NPDs, the C-weighted adjustments with expanded spectra can be applied to standard-spectra A-weighted NPDs.

### D. Time Audible

The Time Audible (TAUD) metric relies on standard values for the reference threshold of human hearing, as well as standard values of human hearing sensitivity. The detectability level, D'L (see Equation 2), is a frequency-specific value that relies on constant values of human aural efficiency and threshold detection.

$$D'L_{total} = 10 \cdot \log_{10}\left(\left[\sum_{band=17}^{40}\left(10^{\frac{D'L_{band}}{10}}\right)^2\right]^{1/2}\right) \tag{2}$$

where D'Lband is the detectability level for each one-third octave frequency band:

$$D'L_{band} = (L_{signal,band} - L_{noise,band}) + \{10 \cdot \log_{10}[\eta_{band}] + 0.5 \cdot 10 \cdot \log_{10}[bandwidth]\} \tag{3}$$

where

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[d] Difference of 2.46 dB for Helicopter A Approach event, 18 foot barrier elevation.
[e] Difference of -0.24 dB at a source to receiver distance of 25,000 feet.

| | |
|---|---|
| $10 \cdot \log_{10}[\eta_{band}]$ | one-third octave band specific constant, |
| bandwidth | the bandwidth of the one-third octave band, |
| $L_{signal,\ band}$ | the un-weighted, one-third octave band sound pressure levels from the spectral class, and |
| $L_{noise,\ band}$ | the addition of the un-weighted, measured one-third octave band ambient levels and the appropriate Equivalent Auditory System Noise (EASN) level. |

Values for reference threshold of hearing are not given below 20 Hz in the ISO standard[6]; therefore, values for 12.5 and 16 Hz were extrapolated via a sixth-order polynomial regression. Similarly, values for frequency-specific receiver efficiency ($\eta_{band}$) below 31.5 Hz, and Equivalent Auditory System Noise (EASN) below 50 Hz were estimated via fourth-order polynomial regression. Using expanded spectra from the Helicopter A approach event, overall detectability D' was unchanged over its value using standard spectra, where both values of D'$L_{total}$ were 70.2. However, the individual one-third octave band containing Helicopter A's MBF was detectable, as its D'$L_{band}$ value exceeded the detectability threshold. Similar results for overall detectability were obtained for Helicopters B and C, where individual low frequency bands were detectable, but had only a negligible impact on overall detectability. Figure 4 shows that much of the low frequency noise from a sample helicopter is masked by the EASN level, which increases quickly below 50 Hz and minimizes the effect of low frequency noise on overall detectability. EASN level decreases above 50 Hz, dropping below 20 dB above 125 Hz, making detection much more likely to occur in the mid-to-high frequency range. Therefore, use of expanded spectra is unlikely to have an effect on TAUD unless there are prominent tones and low background ambient noise in the low frequency bands. Time audible calculations are based on the overall detectability of the aircraft on a particular flight segment, and depend on the value of D'$L_{total}$ to determine the percentage of time the aircraft is audible over the time period of interest.

## 3. CONCLUSIONS

The preliminary study indicates that the use of expanded low frequency spectra has effects on a number of AEDT/INM calculations. A-weighted noise levels and Time Audible computations are minimally affected, whereas C-weighted metrics show the greatest changes. The frequency dependent adjustments, which show the greatest increase between standard and expanded spectra, are applied to the A-weighted NPDs. As there is minimal change these A-weighted NPDs, they could be used in AEDT with expanded-spectral data to better represent the low frequency contributions to these adjustments. The small aircraft sample set limits the applicability of these preliminary results. Although results from all three aircraft are generally similar, several results for the larger Helicopter A stand apart. The addition of more helicopters to this analysis may allow for a better understanding of the generality of these results and, in particular, the effect of aircraft size and weight on the resulting values.

## 4. NEXT STEPS

Expanded spectral data have been measured for two additional helicopters: Helicopter D, an additional two-blade, single engine, two-place light helicopter comparable to Helicopter C, and Helicopter E, a three-blade, single engine, seven-place light helicopter comparable in size to

Helicopter A.  The addition of the above data from these aircraft may allow for more generalization of results, and will allow for a better understanding of the effects of aircraft size and weight on the resulting noise levels, as Helicopter E is comparable to  Helicopter A. In addition, further analysis of the effects of expanded spectra on line-of-sight blockage and TAUD is necessary, including specific analysis with varied ambient noise spectra.

Using the expanded-spectra capability of AEDT, simulations will be run to determine the effects of expanded spectra for the following single events with a variety of meteorological and terrain conditions, and exploring various types of aircraft operations for various noise metrics (A-weighted, C-weighted and TAUD metrics).  Following this, verification and validation studies will be run in AEDT using aircraft and locations where expanded-spectral data are available.  These more complete studies will allow for broader modeling of the effects of expanded spectra. If the above analysis indicates that expanded spectral data should be used in AEDT modeling, recommendations for changes to the spectral class implementation and database will be made.

## 5. ACKNOWLEDGEMENTS

## 6. REFERENCES

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2.  S. Fidell, and R. Horonjeff, <u>A graphic method for predicting audibility of noise sources.</u> Technical Report AFWAL-TR-82-3086, Flight Dynamics Laboratory, Wright-Patterson Air Force Base, Ohio, 1982.

3.  Michael Lau, et al., "Aircraft Source Noise Measurement Studies: 2006-2008 Summary of Measurements, Data and Analysis for the: Cessna 182 Skylane, Cessna 208 Caravan I, Dornier 228-202, Dornier 328-100, Piper PA-42 Cheyenne III, Bell 407, Robinson R44 Raven, Schweizer 300C," Volpe National Transportation Systems Center: Cambridge, MA, September 2009 (Draft).

4.  Society of Automotive Engineers, Committee A-21, Aircraft Noise, Procedure for the Computation of Airplane Noise in the Vicinity of Airports, Aerospace Information Report No. 1845, Warrendale, PA: Society of Automotive Engineers, Inc., 1986.

5.  <u>Specification for Octave Band and Fractional Octave Band Analog and Digital Filters</u>, American National Standard, ANSI S1.11-2004, New York, NY: American National Standards Institute, 2004.

6. <u>Acoustics – Reference zero for the calibration of audiometric equipment – Part 7,</u> <u>International</u> Standard, ISO 389-7, Geneva: International Organization for Standardization, 1998.

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## 7. FIGURES AND TABLES

Table 1. Subject Helicopters

| Aircraft | Passenger Capacity (including pilot) | Main Rotor Blade Count | Main Rotor Blade-Pass Frequency (Hz) | Main Rotor RPM | Max. Gross Weight (lb) |
|---|---|---|---|---|---|
| Helicopter A | 7 | 4 | 27.5 | 412.5 | 5000 |
| Helicopter B | 4 | 2 | 13.6 | 408 | 2400 |
| Helicopter C | 2 | 3 | 23.6 | 472 | 2050 |

Figure 1. Helicopter A Departure, Source Normalized to 1,000 Feet
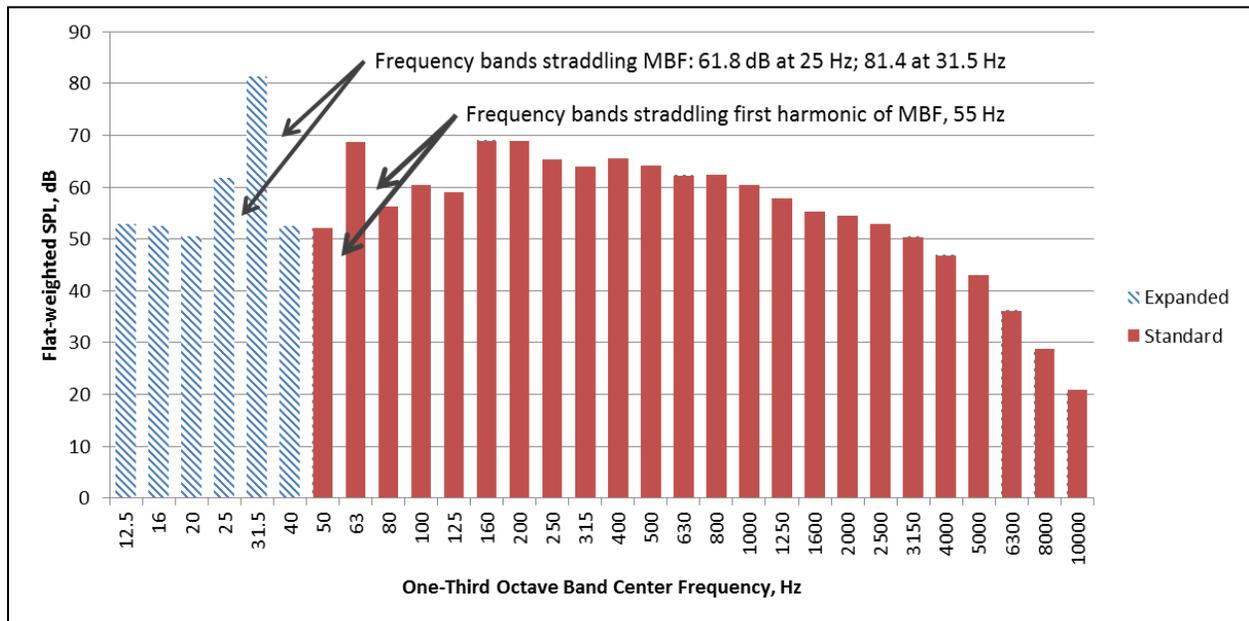
Table 2. Overall SPL, Standard vs. Expanded Spectra, Dynamic Events[f]

| | | Spectrum | Event SPL, dB | | |
|---|---|---|---|---|---|
| | | | Level Flight | Departure | Approach |
| Helicopter A | Flat Weighted | Expanded | 83.98 | 82.63 | 88.25 |
| | | Standard | 82.54 | 76.42 | 82.38 |
| | | difference | 1.44 | 6.21 | 5.87 |
| | A-weighted | Expanded | 75.34 | 70.05 | 76.61 |
| | | Standard | 75.34 | 70.05 | 76.60 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 83.13 | 80.48 | 86.21 |
| | | Standard | 82.32 | 76.25 | 82.32 |
| | | difference | 0.82 | 4.23 | 3.89 |
| Helicopter B | Flat Weighted | Expanded | 81.35 | 77.66 | 80.24 |
| | | Standard | 77.23 | 74.07 | 78.41 |
| | | difference | 4.12 | 3.59 | 1.83 |
| | A-weighted | Expanded | 70.74 | 66.64 | 72.06 |
| | | Standard | 70.74 | 66.64 | 72.06 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 78.38 | 75.09 | 78.95 |
| | | Standard | 77.00 | 73.97 | 78.34 |
| | | difference | 1.38 | 1.12 | 0.60 |
| Helicopter C | Flat Weighted | Expanded | 72.73 | 72.55 | 74.25 |
| | | Standard | 70.54 | 70.68 | 71.69 |
| | | difference | 2.20 | 1.87 | 2.56 |
| | A-weighted | Expanded | 64.68 | 65.39 | 65.52 |
| | | Standard | 64.68 | 65.39 | 65.52 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 71.22 | 71.10 | 72.56 |
| | | Standard | 70.42 | 70.57 | 71.56 |
| | | difference | 0.80 | 0.53 | 1.00 |

[f] Values calculated at a source-to-receiver distance of 1,000 feet.

Table 3 Overall SPL, Standard vs. Expanded spectra, Static events[4]

| | | Spectrum | Event SPL, dB | | | |
|---|---|---|---|---|---|---|
| | | | Flight Idle | Ground Idle | HIGE[g] | HOGE[h] |
| Helicopter A | Flat Weighted | Expanded | 66.99 | 55.37 | 70.69 | 69.53 |
| | | Standard | 66.99 | 55.37 | 70.69 | 69.53 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | A-weighted | Expanded | 66.97 | 55.86 | 70.49 | 68.52 |
| | | Standard | 66.97 | 55.86 | 70.49 | 68.58 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 66.89 | 55.17 | 70.64 | 69.49 |
| | | Standard | 66.89 | 55.17 | 70.64 | 69.72 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | -0.22 |
| Helicopter B | Flat Weighted | Expanded | 64.27 | 64.51 | 69.12 | 68.90 |
| | | Standard | 64.27 | 64.51 | 69.12 | 68.90 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | A-weighted | Expanded | 60.73 | 59.42 | 67.52 | 67.60 |
| | | Standard | 60.73 | 59.42 | 67.52 | 67.60 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 64.22 | 64.46 | 69.08 | 68.87 |
| | | Standard | 64.22 | 64.46 | 69.08 | 68.87 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| Helicopter C | Flat Weighted | Expanded | 55.98 | 46.88 | 59.86 | 63.76 |
| | | Standard | 55.98 | 46.88 | 59.86 | 63.76 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | A-weighted | Expanded | 54.97 | 44.50 | 59.48 | 62.50 |
| | | Standard | 54.97 | 44.50 | 59.48 | 62.50 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |
| | C-weighted | Expanded | 55.85 | 46.74 | 59.74 | 63.73 |
| | | Standard | 55.85 | 46.74 | 59.74 | 63.73 |
| | | difference | Less than 0.1 | Less than 0.1 | Less than 0.1 | Less than 0.1 |

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[g] Hover In Ground Effect event
[h] Hover Out-of-Ground Effect event

Figure 2. Difference (Standard - Expanded) in Atmospheric Absorption Adjustment for a Sample Helicopter
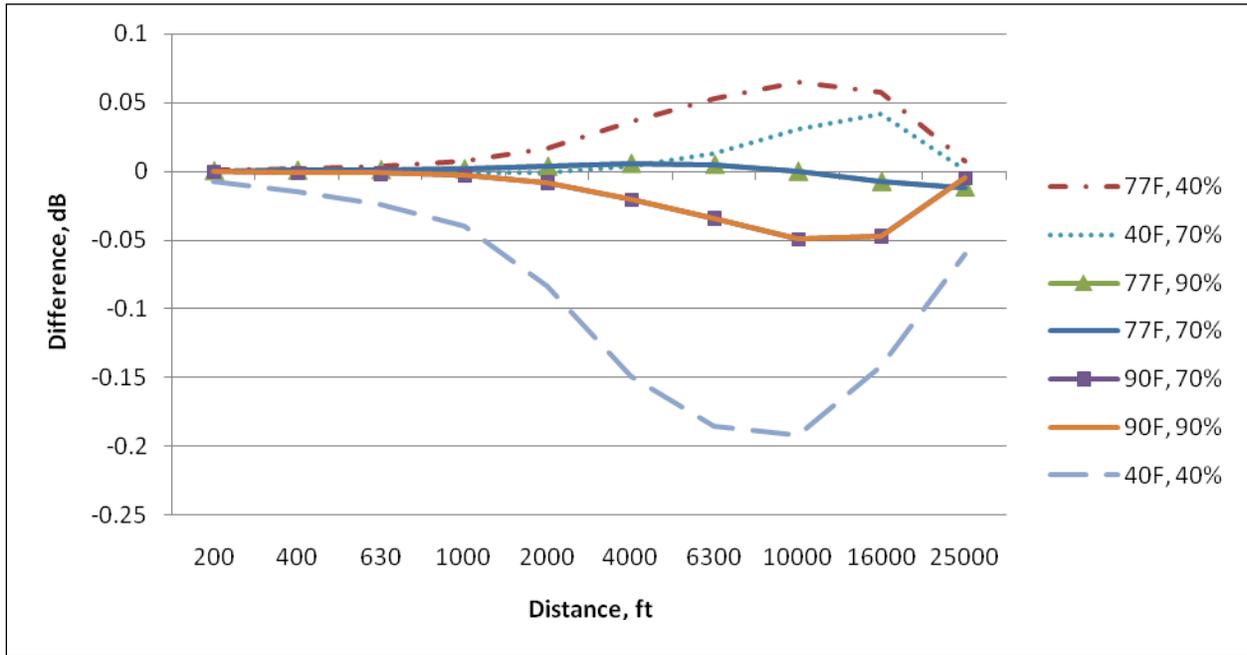


Table 3. Line of Sight Blockage Adjustment for a Sample Helicopter, Standard vs. Expanded Spectra, 1000 foot Source-Receiver Distance

| Barrier Elevation, ft | Path Length Difference ($\delta_0$), ft | $LOS_{ADJ}$, dB | | |
|---|---|---|---|---|
| | | Standard spectra | Expanded spectra | Difference |
| 6 | 0.1 | -4.57 | -3.65 | -0.91 |
| 18 | 1.0 | -2.76 | -0.38 | -2.38 |
| 40 | 5.0 | less than 0.1 | less than 0.1 | less than 0.1 |
| 57 | 10.0 | less than 0.1 | less than 0.1 | less than 0.1 |
| 131 | 50.0 | less than 0.1 | less than 0.1 | less than 0.1 |
| 192 | 100.0 | less than 0.1 | less than 0.1 | less than 0.1 |

Figure 3. Comparison of the Effects of Expanded Spectral Data on A- and C-weighted NPDS for a Sample Helicopter
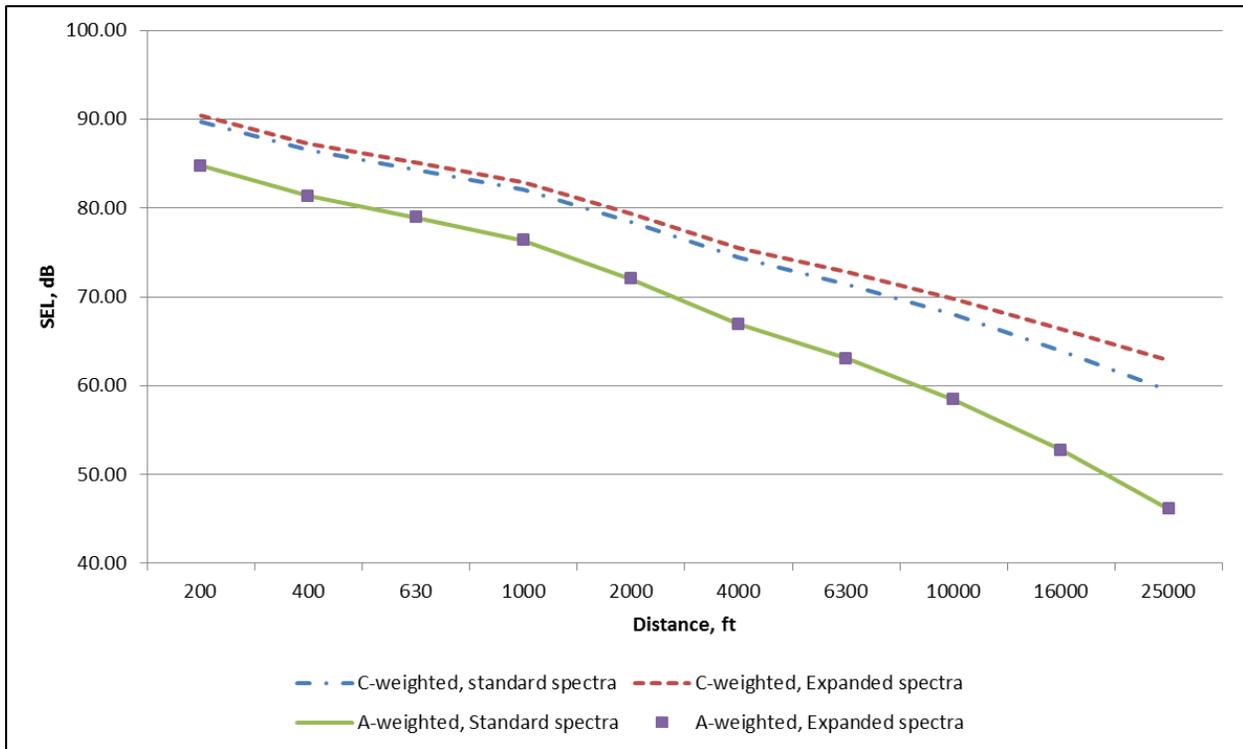
Figure 4.  Comparison of a Helicopter Source, Ambient and the Equivalent Auditory System Noise Spectra